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EVALUATION OF THE DYNAMIC CUTOFF RIGIDITY MODEL USING DOSIMETRY DATA FROM THE STS-28 FLIGHT

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ABSTRACT

We have a developed a dynamic cutoff rigidity model based on computed world grids of vertical cutoff rigidities derived from employing the Tsyganenko magnetospheric model. The dynamic range of this model covers all magnetic activity levels specified by integer values of the Kp magnetic index. We present comparisons of the measured dose observed on the space shuttle during the August 1989 solar proton event with the dose computed from solar particles predicted to be allowed through the magnetosphere to the space shuttle position. We find a one-to-one correspondence between the portion of the orbit predicted to be subjected to solar protons and the portion of the orbit where solar particle dose measurements were obtained. © 2003 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

As a result of an intensive calculation effort (~1000 node hours on an IBM SP2) we have a complete set of world grids of vertical cutoff rigidities each 5° in latitude and 5° in longitude for a spacecraft orbiting at 450 km. This reference set of world grids covers all magnetic activity levels from super quiet to extremely disturbed (i.e., Kp indices ranging from 0 to 9$^+$). These world grids of vertical cutoff rigidities were obtained by particle trajectory tracing in model magnetospheres.

Magnetospheric Models

The model magnetospheres were derived from the Tsyganenko (1989) magnetospheric field model combined with the International Geomagnetic Reference Field for epoch 1995.0 (Sabaka et al., 1997) in the manner described by Flückiger and Kobel (1990). The Boberg et al. (1995) extension was used to describe the magnetospheric fields for magnetic activity levels exceeding Kp values of 5. The magnetic fields utilized (both the IGRF and the Tsyganenko model) were defined for 1 January 1995.

The Tsyganenko (1989) magnetospheric field model describes the magnetospheric field topologies for the Kp magnetic indices from 0 to 5. We have utilized the Boberg et al. (1995) extension to include the probable effect of additional ring currents during severe magnetic storm conditions. For convenience we have labeled these as Kp 6 through 10 for Dst increments of -100 nT.

Cutoff Rigidity Determination Procedure

Cosmic ray trajectory calculations were initiated in the vertical direction from a distance of 6821.2 km from the geocenter (450 km altitude above the average earth radius of 6371.2 km). The "sensible" atmosphere of the earth was considered to extend 20 km above the international reference ellipsoid, and any trajectory path that came lower than this distance was considered to be re-entrant and hence forbidden. In this work, "vertical" is the direction radial from the earth center. The trajectory-tracing technique employed was developed by Kobel (1990) and utilizes the Bulirsch-Stoer numerical integration technique (Stoer and Bulirsch, 1980; Press et al., 1989) to

minimize the number of steps required in a charged particle trajectory computation. Each step length was about 1% of a gyro-distance (Smart and Shea, 1981), the distance the particle of the specified rigidity would travel during one gyration in a uniform magnetic field of the same intensity.

The cutoff rigidities are determined by calculating charged particle trajectories at discrete rigidity intervals starting with a rigidity value high above the highest possible cutoff and decreasing the rigidity to a value that satisfied our criteria that the lowest allowed trajectory had been calculated. As these calculations progress down through the rigidity spectrum, the results change from the easily allowed orbits to a complex structure of allowed, forbidden, and quasi-trapped orbits (loosely called penumbra) and finally to a set of rigidities where all trajectories intersect the solid earth. As a result of these trajectory calculations we determined the calculated upper cutoff rigidity (R_U) which is the rigidity value of the highest allowed/forbidden pair of adjacent cosmic ray trajectories, the calculated lowest cutoff rigidity (R_L) which is the rigidity value of the lowest allowed/forbidden pair of adjacent cosmic ray trajectories, and an "effective cutoff rigidity" (R_C) that allows for the transparency of the penumbra. (See Cooke et al., 1991, for definitions of cosmic ray cutoffs.) Rigidity intervals of 0.01 GV were used for trajectories between R_U and R_L to provide a reasonable sample of the cosmic ray penumbra. The effective cutoff rigidity R_C was found by summing the allowed orbits through the penumbra as described by Shea et al. (1965).

THE DYNAMIC CUTOFF RIGIDITY MODEL

The result of this extensive calculation effort is a dynamic geomagnetic cutoff rigidity model for spacecraft altitudes. These updated cutoff rigidity models have a 5 degree by 5 degree world grid spacing which results in better fits to the available data than the course 5 degree in latitude by 15 degree in longitude world girds previously reported by Smart et al. (1999a,b,c). A comparison of the components of this dynamic cutoff rigidity model with vertical cutoff rigidities calculated using only an internal geomagnetic field for the same altitude (Smart and Shea, 1997) show that these magnetospheric cutoff rigidity values are consistently lower in magnitude, even for the Kp=0 case. Iso-rigidity contours for various magnetic activity levels ranging from very quiet magnetic conditions (Kp = 0) to very disturbed (Kp = 8) are presented in the following figures. The iso-rigidity contours presented in these figures are the average of cutoff calculations at four different universal times, 00 UT, 06 UT, 12 UT and 18 UT. At the cutoff rigidities presented in these figures (>1 GV), the local time effects at a specific position are not significant. However, at low rigidities (in the energy range of ~10 MeV or a rigidity value of ~0.14 GV), the longitude shift in the high latitude iso-rigidity contours can be of the order of an hour angle (i.e. 15 degrees).

Inspection of Figures 1-4 show the equatorward movement of the cutoff rigidity contours as the magnitude of the magnetic index activity increases. Note that the 15 GV contour visible in Figure 1 (the Kp = 0 case which represents a very quiet magnetosphere) is not present in Figure 3 (the Kp = 5 case which represents an active magnetosphere). Another indication of the reduction in geomagnetic cutoff as a function of magnetic activity can be obtained by inspection of the 11 GV contour line in each figure. This 11 GV contour line is distinct in both the northern and southern hemisphere in Figures 1-3. However, in Figure 4 (the Kp = 8 case representing a very disturbed magnetosphere), the 11 GV contour has "closed" and does not exist in the longitude interval between ~280 and ~315 degrees East longitude.

Rigidity is not the most convenient unit for use with energetic particle data since most energetic particle measurements are in units of energy. For comparison purposes, we have selected the invariant latitude calculated from the internal geomagnetic field as a common parameter. We have interpolated through our world grids of vertical geomagnetic cutoff rigidities for each magnetic activity level to determine proton cutoff energy contours as a function of invariant latitude and obtained an average invariant latitude for each energy. The proton cutoff invariant latitudes as a function of magnetic activity are illustrated in Figure 5. These curves indicate an almost linear relation between the proton cutoff energy with latitude in the range from about 10 MeV to a few hundred MeV. We note that the change of proton cutoff energy with Kp is relatively uniform over the range of the original Tsyganenko (1989) model, but the cutoff changes introduced by the Boberg (1995) extension is non-linear with the Dst increment.

VERTICAL CUTOFF RIGIDITIES AT 450 KM
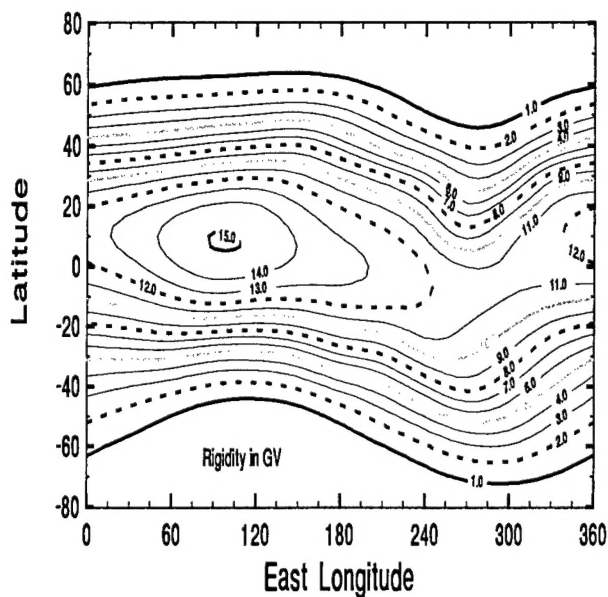
Rc   Tsyganenko model   Kp = 0

Fig. 1. Cutoff rigidity contours at 450 km for Kp = 0.

VERTICAL CUTOFF RIGIDITIES AT 450 KM

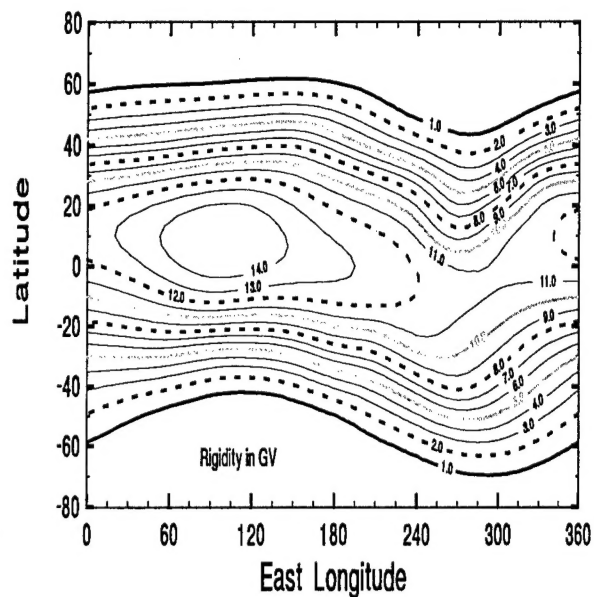Rc   Tsyganenko model   Kp = 5

Fig. 3. Cutoff rigidity contours at 450 km for Kp = 5.

VERTICAL CUTOFF RIGIDITIES AT 450 KM
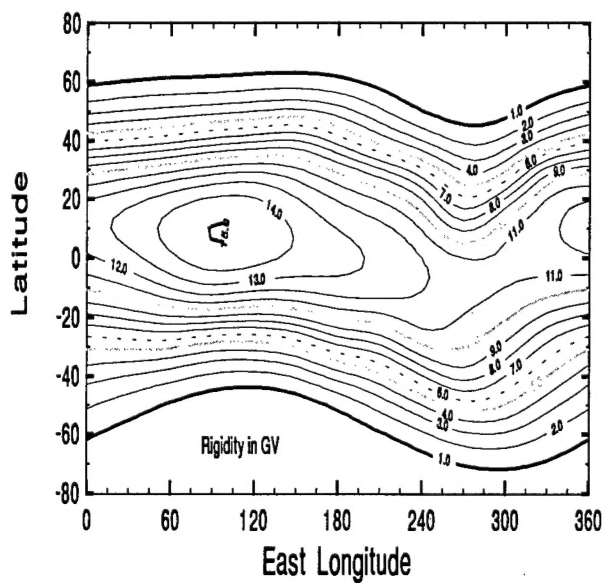
Rc   Tsyganenko model   Kp = 2

Fig. 2. Cutoff rigidity contours at 450 km for Kp = 2.

VERTICAL CUTOFF RIGIDITIES AT 450 KM

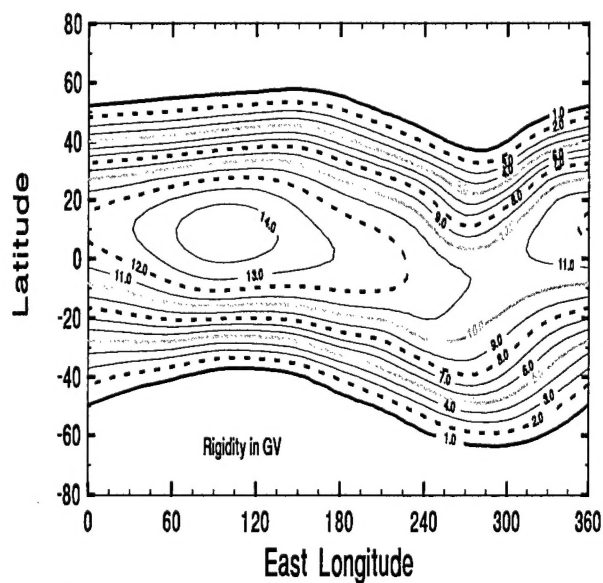Rc   Tsyganenko model   Kp = 5; Dst -300 (Boberg et al. extension)

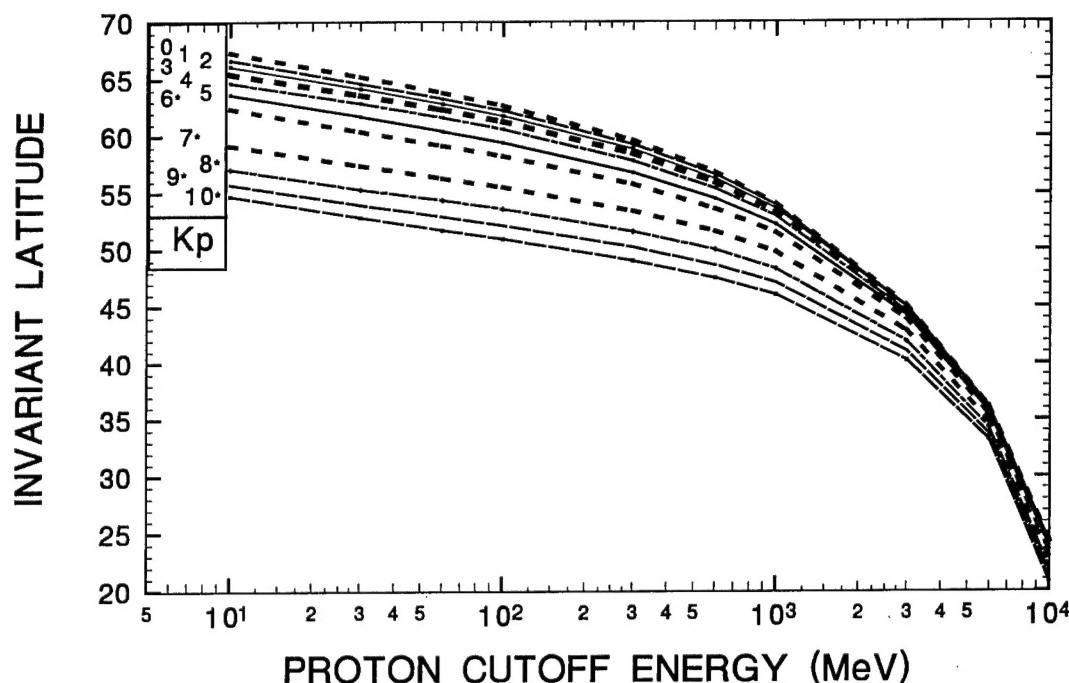Fig. 4. Cutoff rigidity contours at 450 km for Kp = 8

Fig. 5. Change in effective vertical cutoff energy at 450 km altitude as a function of magnetic activity.

COMPARISONS WITH SPACECRAFT DOSIMETRY DATA

The STS28 space shuttle flight in August 1989 was in a 57° inclination orbit and carried a dosimeter that provided data every 10 seconds of the mission. This flight encountered the beginning of the large solar proton event sequence that began on 12 August 1989 at 15 hours UT and recorded dosimetry data due to solar particles whenever the orbit passed into the low cutoff region at high magnetic latitudes. The STS28 flight was completed on 13 August with the shuttle landing shortly after 13 UT. We will use this dosimetry data acquired during an actual space flight as a method of evaluating the accuracy of the dynamic cutoff rigidity model. During the time the vehicle encountered solar protons, the geomagnetic activity level as quantified by the Kp index varied between 1 and 3.

The comparison method will be to apply this dynamic cutoff rigidity model to predict the solar proton transmission through the magnetosphere to the position of the space shuttle (latitude, longitude and altitude) each minute of the shuttle fight during its encounter with the solar proton event. The solar particle flux predicted to arrive to the skin of the space shuttle at each position was transmitted through a model of the physical mass of the shuttle structure to the dosimeter location to generate a computed radiation dose rate for comparison with the actual measured dose rate. A more detailed description of this radiation dose rate calculation method is given by Golightly and Weyland (1997). The general procedure was:

1. Determine (by interpolation in the appropriate 5° x 5° world grid of cutoff rigidities) the vertical cutoff proton energy at the spacecraft position for each minute of the solar proton event encounter.
2. Model the GOES measured solar proton flux as the differential flux impacting the magnetosphere as an exponential fit to the solar particle flux between 30 and 100 MeV.
3. Determine the differential solar particle flux at energies exceeding the proton cutoff energy at the spacecraft position.
4. Reduce the free space omni-directional flux to account for "earth shadowing" in low-earth orbit.
5. Attenuate the incident solar particles through the spacecraft mass distribution.
6. Calculate the dose rate from the attenuated solar proton flux spectrum penetrating to the dosimeter location.

If the cutoff rigidity has the proper value, then the computed dose rate and the measured dose rate should be very similar. The comparison is presented in Figure 6.

An inspection of Figure 6 shows a one-to-one correspondence between the time periods of computed radiation dose rate due to solar protons being allowed through the magnetosphere to the position of the space shuttle and the measured dose rate in the vehicle, even for very small doses. A detailed examination of the computed dose rate and the observed dose rate shown in Figure 6 indicates an "overshoot" in the computed dose rate at very low cutoff values. Our investigation into the cause of this overshoot indicates that it is not a result of the geomagnetic cutoff because at the time and position of the overshoot the geomagnetic cutoff values are very low, below the cutoff energy of the mass shielding. Our initial conclusion is that it is the result of using the simple exponential fit between 30 MeV and 100 MeV solar particle flux to characterize the entire solar particle spectrum. This simple exponential simulation of the solar proton spectrum apparently generates an excess of high-energy protons that are probably not present in the actual solar particle spectrum.

Figure 7 illustrates the times when we compute that the solar protons with energy >100 MeV have access to the STS28 orbit. We also note that there is a measurable dose from solar protons when the omni-directional flux at the spacecraft position with energies >100 MeV exceeds 1 $(cm^2\ s)^{-1}$.
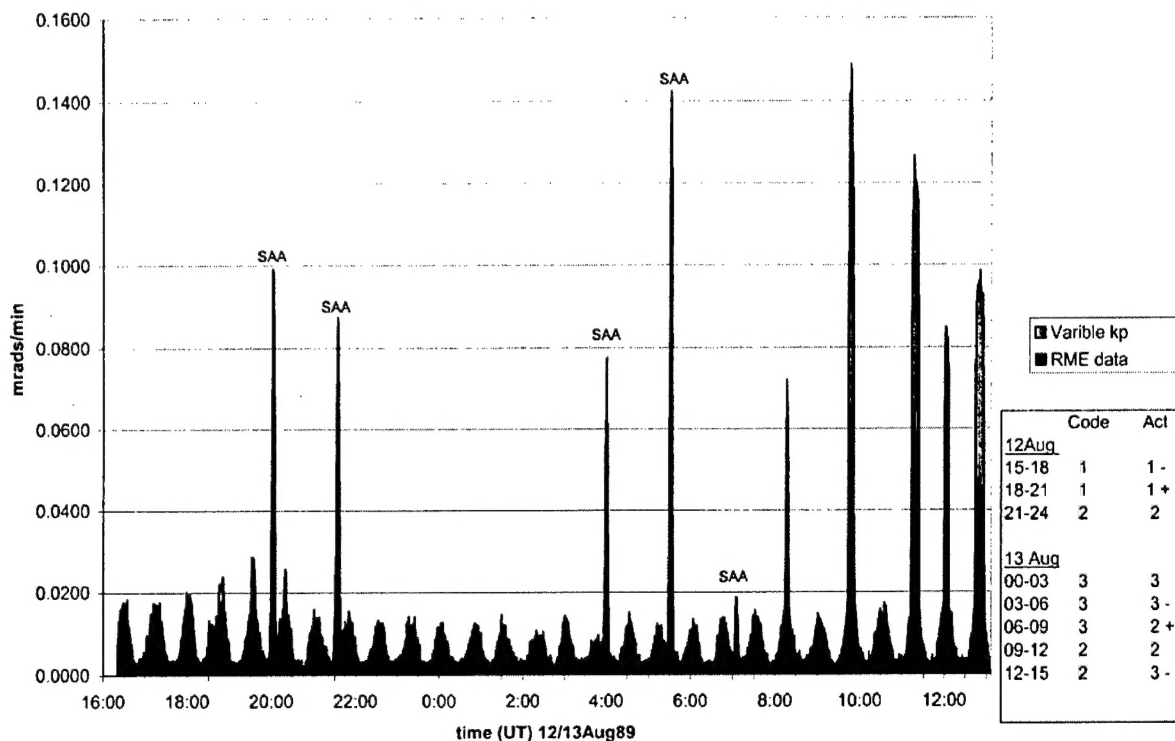

Fig 6. Comparison of computed and observed radiation dose rate during the STS28 encounter with the 12/13 August 1989 solar proton event. The dose due to the trapped radiation is identified as SAA. Note the small regular modulation of the dose rate due to galactic cosmic radiation each time the spacecraft trajectory encounters the high latitude phase of each orbit (reduced geomagnetic cutoffs). The primary exposure to solar protons occurred at 08:13-08:20, 09:42-09:53, 11:13-11:26, 11:59-12:09, and 12:44-12:58 UT.

CONCLUSION

A comparison of the computed and measured radiation dose rate on the STS28 space shuttle encounter with the 12-13 August 1989 solar proton event shows that the dynamic cutoff rigidity model correctly predicts when solar particles were allowed through the magnetosphere to the spacecraft position. There is a one-to-one correspondence between the portion of the orbit predicted to be subjected to solar protons and the portion of the orbit where the radiation dose attributed to solar particles was obtained.
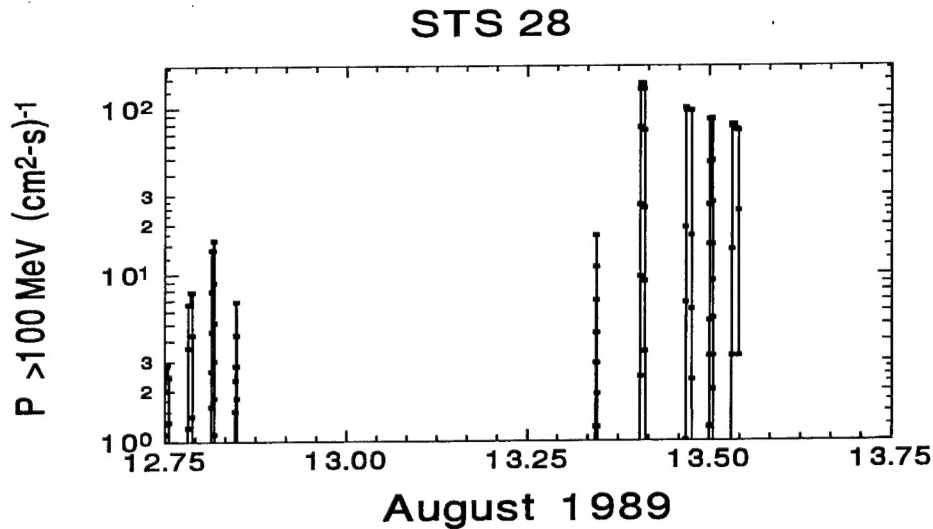
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Fig. 7. The predicted >100 MeV solar particle access to the STS28 orbit.

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